LARGE MOTOR SPECIFICATION AND SELECTION

by

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William H. Miller founded REM Technologies, Incorporated, in 1984. He serves as President and Principal Engineer. REM provides numerous engineering services to motor and generator users.

Mr. Miller graduated from Cornell University as a Mechanical Engineer. He joined the Elliott Company, as a Development Engineer, and concentrated on the analysis of bearings, seals, and rotor vibrations. This work gained him his first patent award for invention of a high pressure shaft seal.

In 1976, he joined Ingersoll Rand Company. While there, he co-authored a paper and was awarded the American Society of Lubrication Engineer's Walter D. Hodson Award. Mr. Miller later joined Mechanical Technology, Incorporated in Latham, New York, where his research and development in the area of compliant foil bearings produced four new and patented designs to improve foil bearing performance.

Mr. Miller went to General Electric Company's Materials and Processes Laboratory in Schenectady, New York as a Rotordynamicist and Bearing Analyst. He transferred to the Large Motor and Generator Department as Manager of Advanced Quality Control Engineering. He was responsible for the design, implementation, and auditing of the department's Government, Nuclear, and Commercial Quality Control Programs. He was later Manager of Mechanical Design, and then Subsection Manager of Mechanical Design of Medium Motor Redesign Project. His work in mechanical design has resulted in seven patents, and four pending.

INTRODUCTION

The induction motor has been the work horse of industry for many years. It has achieved this position by virtue of its ruggedness, and relative low cost. Induction motors include the popular squirrel cage and the versatile wound rotor motor. In addition, derivatives of these basic motors such as multispeed, high inertia starting have been developed for special applications. The synchronous motor is quite similar to the induction motor in its general arrangement. The synchronous motor is seldom used in the small horsepower range because of its cost disadvantage as compared to the induction motor. This discussion will be directed to specification and selection of large motors of approximately 300 hp and above.

PRINCIPLES OF OPERATION

Stator

Polyphase motors have stators and stator windings (armature windings) which are essentially the same for either an induction or synchronous motor (Figure 1). In the polyphase motor, currents circulating through the distributed stator winding produce a flux pattern of alternate north and south magnetic poles that progresses around the air gap at a speed directly proportional to the frequency of the power supply and inversely proportional to the number of pairs of poles in the winding.

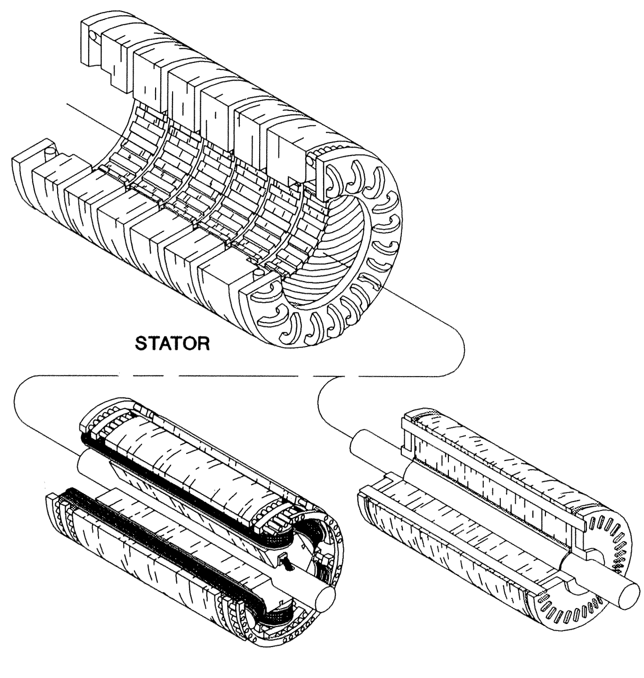

Figure 1. Details of Motor Stator and Rotor Construction.

The electrical analysis for this phenomenon is quite similar to that for a transformer, and thus, it has become the "practice" to refer to the stator or line side of the motor as the primary and the rotor side of the machine as the secondary.

INDUCTION MOTOR

If the secondary conductors are arranged like bars of a squirrel cage, and if the squirrel cage is arranged to allow rotation, the force of the interaction of the stator and rotor flux on the conductors will rotate the squirrel cage. In practice, the uninsulated bars of the squirrel cage are embedded axially in a laminated iron rotor close to the periphery of the rotor and are connected together through a suitable short-circuiting ring at each end of the rotor. This simple construction makes the squirrel cage motor the most rugged and the least expensive of all types of induction motors.

Variations in rotor bar design give wide variations in the performance characteristics of the induction motor, especially torque and current versus speed characteristics. The electrical industry builds three fundamental types of squirrel cage motors. They are: (1) normal starting current and torque; (2) normal starting current, high starting torque; and (3) low starting current, high starting torque (high slip).

General Principles

The following are general principles of induction motor operation. They are presented because they will enable one to better understand the application of induction motors.

- All torques produced by an induction motor are proportional to the square of the voltage applied to the motor terminals.
- High rotor bar resistance produces high starting torque (for line amperes drawn) but results in lower running efficiency.
- Low rotor bar resistance produces high full load speed (low slip and low starting torque) and results in high efficiency.
- The rotor frequency and voltage is proportional to slip. Hence, both are zero at synchronous operating speed, but increase to a maximum value at zero speed.
- The *slip* at which maximum torque is produced is proportional to rotor bar resistance.
- The rotor losses are proportional to slip and are all inside the rotor of a squirrel cage motor. However, on a slip ring motor, the secondary losses divide in proportion to the inherent rotor winding resistance and the connecting external resistance.
- At the completion of the acceleration of the rotor the kinetic energy of the rotating parts at full speed is exactly equal to the heat energy generated in the rotor of an induction motor by the accelerating component of motor torques and secondary current. This is true independent of the shape of the speed torque curve and thus does not depend upon the type of motor.

Torque Definitions

The speed torque curve is the fundamental characteristic of any induction motor. The various points on the speed torque curves (Figure 2) are defined by National Electrical Manufacturers Association (NEMA) as follows:

Locked-rotor Torque—The minimum torque which a motor will develop at rest with rated voltage applied at rated frequency.

Pull up Torque—The minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown torque occurs. For motors which do not have a definite breakdown torque, the pull up torque is the minimum torque developed up to rated speed.

Breakdown Torque—The maximum torque which a motor will develop with rated voltage applied at rated frequency without an abrupt drop in speed.

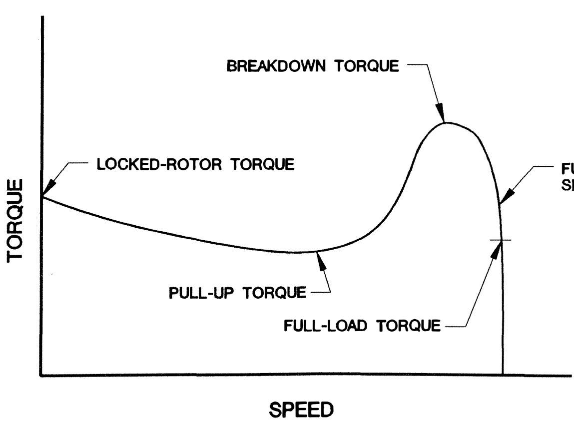

Figure 2. Induction Motor Speed Torque Characteristic.

Full load Torque—The torque necessary to produce rated horsepower at full load and full speed. The full load torque is equal to the horsepower times 5250, divided by the full load speed.

INDUCTION MOTOR

NEMA Design B
Normal Starting Current and Torque

The general purpose squirrel cage motor with normal starting current and torque may be referred to as a Design NT in some standards. In smaller ratings it is identified as NEMA Design B. The low-resistance rotor winding (aluminum or copper) gives low slip (about 0.5 to 1.5 percent at full load). High efficiency can be obtained because of low rotor losses. Normal starting torque falls between 60 and 100 percent of rated torque depending on size and speed. As horsepower ratings increases for the number of poles (in other words, for a given speed) the starting torque tends to decrease. Breakdown torque is between 175 and 200 percent and occurs at relatively low slip. Normal "in rush" starting current is in the order of 600 to 650 percent of full load current. Since the Design B motor has low slip (with the speed variation between no load operation and full load about 0.5 to 1.5 percent) it is generally referred to as a constant speed motor.

The application for this type motor can be characterized as (1) constant speed; (2) not too frequent starting duty; and (3) no slow speed running. Machines such as centrifugal compressors, pumps, blowers, and motor-generator sets are typical applications for this type motor.

NEMA C
Normal Starting Current, High Starting Torque

If a machine is started fully loaded, the motor must have sufficient starting torque to take care of both normal load torque and breakaway torque requirements. The NEMA C motor has normal starting current and operates at about the same slip at full load as the NEMA B machine, yet has high starting torque (about twice full load torque). It may be referred to as a Design HT in some standards. The characteristics are accomplished by the unique shape of the bars used in the squirrel cage rotor.

The applications for this type of motor are those that require running characteristics of the NEMA B but also require the extra torque at starting. Typical applications include coal pulverizers, agitators, rock crushers, stirring machines, conveyor drives, and pump and reciprocating compressor starting under load.

NEMA D
Low Startinq Current and High Starting Torque

The NEMA D motor is characterized by a high starting torque, high slip and low starting current. Usual starting torque ranges between 250 and 300 percent with a usual value of starting current between 400 and 550 percent of full load current. The NEMA D is also a high slip motor and can be obtained with slips in two ranges: five to eight percent or eight to thirteen percent. Based on the principles listed earlier, it can be concluded that the NEMA D motor has higher resistance rotor bars, and hence, lower operating efficiency. However, it has an advantage of a lower starting current. The high rotor losses affect the frame sizes of this type of motor. Hence, the designer must use a larger frame than for the NEMA B or NEMA C motor for a similar rating.

The NEMA D motor is used for accelerating fairly high WK^2 loads, especially when the period of full speed, full load operation is limited such as ore or coal car pulling operations or elevator applications.

Wound Rotor Motor (Slip-ring)

Wound rotor motors are used where it is necessary to start the motor with a current inrush limitation lower than that which can be met successfully by a squirrel cage motor or a synchronous motor. Wound rotor motors are reliable drives for large ball mills, large presses, variable speed pumps, rolling mills, centrifugal refrigeration compressors, and similar applications. The wound rotor motor is an induction motor with an adjustable speed torque characteristic. This adjustment is accomplished by using a three-phase rotor winding similar to the stator winding. One end of each phase is brought out to a slip ring on the motor shaft. Through stationary brushes which contact with the slip rings, any desired value of resistance may be added to the secondary circuit. The value of maximum torque (normally between 200 percent and 250 percent) is not affected by a change in resistance. However, the slip or speed at which the maximum torque occurs is dependent upon the secondary resistance. The secondary that gives rated torque at zero speed is called the per unit or 100 percent ohms. Similarly, 50 percent ohms which gives rated torque at 50 percent speed and 70 percent ohms which gives rated torque at 30 percent speed. Hence, by varying the secondary resistance, it is possible to obtain an infinite variation of inrush current *vs* starting torque combinations.

The motor's adjustable speed characteristic is accomplished by changing external resistance. If considerable resistance is added in the secondary, the speed-torque characteristic slopes back such that speed regulation is poor. Since load current is proportional to torque, regardless of external resistance over the straight part of the characteristic, 100 percent torque represents 100 percent current at any speed setting. If the loss dissipating ability of the motor was the same at any speed, the motor would be a *constant torque* motor. However, due to reduced cooling action, the standard open drip proof motor is only capable of 80 percent torque at 50 percent speed.

SPECIAL INDUCTION MOTORS

Multispeed Motors

The squirrel cage motor is essentially a constant speed machine. Many systems which require adjustable speed have been handled by "multispeed" induction motors having two, three, or four definite operating speeds. The various speed combinations are obtained by the following means: (1) single windings, (2) superimposed windings, (3) or a combination of (1) and (2).

A single stator winding may be reconnected to give two speeds in the ratio of 2:1. The lower of the two speeds is obtained from the higher speed arrangement by reversing the connections to alternate poles in the stator winding, which, as a "consequence," induces additional poles intermediate to the original ones. Doubling the number of poles in this way reduces the synchronous speed of the motor by one-half. The changing of poles is accomplished simply by external reconnection of the six stator terminal loads.

A "superimposed" or second stator winding, having the correct number of poles for the desired second speed, often may be added in the slot above the first winding.

The physical size of a multispeed motor depends, on the torque characteristics required and the type of enclosure required. The machine size decreases as follows: (1) constant horsepower; (2) constant torque; and (3) variable torque.

MOTOR MODIFICATIONS FOR STARTING

Full voltage starting of induction motors is necessary in order to obtain simplicity and economy in the starting equipment. All modern induction motors are designed to withstand the application of full voltage at standstill without damage to the motor windings. However, larger motors have full-voltage starting currents which may be objectionable on weak power systems. The three usual methods of reduced-voltage starting used to reduce the current drawn by the motor during motor starting are: (1) the auto-transformer method, (2) the series resistor method, and (3) the series reactor method. These methods do not require modification of the motor in order to be used.

In addition to the foregoing, three other methods for reducing the starting current drawn by a motor have been used which are:

- the series-parallel method requires the proper number of sections in each phase of the motor winding as well as adequate leads;
- the wye-delta method requires extra motor leads and a motor winding designed for delta connection for normal operation; and
- part winding method requires two parallel windings per phase, the proper number of leads, and, in addition, other design problems must be considered.

Usually, these methods require modification of the motor windings. Hence, if they are to be used, the selected method must be specified at the time the motor is ordered.

All of the above methods, either reduced voltage or special winding arrangement result in a considerable reduction in available torque during the starting cycle. Therefore, the starting torque requirements must be carefully considered in selecting and specifying a motor application.

SYNCHRONOUS MOTOR

The synchronous motor is a dependable type of motor drive with wide application in industry. Because the synchronous motor is seldom used in the small horsepower range, many people become uneasy when faced with the task of specifying, selecting, or installing a synchronous motor.

The synchronous motor is quite similar to the induction motor in its general arrangement. Synchronous motors are either very large in rating, or low in speed relative to the normal induction motor. Typically, the synchronous motor has a large diameter and short core length when compared with the induction motor.

SYNCHRONOUS MOTOR ROTOR DESIGN

The rotor of the synchronous motor differs considerably from the induction motor rotor. The rotor has salient poles corresponding to the number of stator winding poles. During steady-state operation, there is no average relative motion between rotor pole and the stator flux pole. Hence, there is no voltage induced in the rotor by the mutual flux. Therefore, excitation does not come from the AC line. Instead, the poles are wound with many turns of copper wire. When a direct current is circulated through the winding, alternately north and south magnetic flux poles are produced. Until recently the DC excitation had to be applied to the field through the use of brush rigging and slip rings. More recently, brushless excitation systems with SCR control have been utilized to minimize maintenance and improve regulation.

Should the rotor be at standstill when direct current is applied to the field winding, the interaction of the line frequency stator flux and the rotor flux will provide a large oscillating torque. However, the rotor will not accelerate. Hence, in order to start a synchronous motor, it is necessary to embed a number of bars in each pole and connect these bars at each end to form a squirrel cage winding similar to that of the induction motor. Further, the field winding must be disconnected from the DC supply and shorted, usually through an appropriate resistor. By proper design of the size, material, and spacing of the bars in the squirrel cage (often called "amortisseur" or "damper" winding), sufficient induction motor type torque is developed to accelerate the rotor to nearly full load speed.

If the rotor has reached sufficient speed and then direct current is applied to the field winding, the motor will pull into synchronism with the rotating stator flux. The pull in torque of a synchronous motor is the maximum constant load torque against which the motor will pull load inertia (WK^2) into synchronism when DC field excitation is applied.

The average pull in torque is a function primarily of the squirrel cage winding characteristics. However, the secondary effect of the external shorting resistor and field winding resistance make important contributions to the speed attainable on the starting (squirrel cage) winding with a given load applied to the motor. Also, because of the salient pole effect, the instantaneous pull in torque varies somewhat from the average value depending upon the load angle between the axis of the rotor and stator poles.

There are differences in control and motor protection of the synchronous motor as compared to the induction motor which are related to the rotor construction. Since the DC excitation is required for synchronous operation, protection against loss of excitation field and loss of synchronism must be provided. During starting, the control equipment must automatically and accurately ensure that the rotor speed has reached a proper value and further, that the proper load angle between rotor and stator flux exists before the DC field excitation is applied. Since the synchronous motor squirrel cage starting winding must only accelerate the total WK^2 and load, and not provide the load torque continuously, the synchronous rotor's squirrel cage thermal capability, and, hence its stall time are generally much less than for an induction motor. Hence, special protection for the squirrel cage must be provided.

However, since the synchronous motor stator windings, bearings, and enclosure are essentially the same as the induction motor, protection schemes for these components are basically the same.

WHY SYNCHRONOUS MOTORS

Better economy is behind the use of synchronous motors in many of the applications of the synchronous motor in industry. The four most common reasons for specifying synchronous motors are to:

- take advantage of the inherent high efficiency;
- obtain power factor correction;
- obtain special starting characteristics; and
- obtain special performance characteristics.

Of these four advantages, the first two have a direct bearing on the overall cost of plant operation.

High Efficiency

With today's ever increasing energy costs, substantial savings can be realized from the lower operating cost of the synchronous motor. When motor efficiency becomes the primary consideration in choosing a motor, a 1.0 power factor (pf) synchronous motor is usually the solution. Since no kilovolt amperes (KVAR) is required, only real power, the line current is a minimum, resulting in less I^2R loss in the motor armature (stator) windings. Also, since the field current required is at the practical minimum, there is less I^2R loss in the rotating field winding as well. If special high-torque situations are expected, the lower losses in both the armature and field permits synchronous 1.0 pf ratings to be designed in smaller frames than corresponding 0.8 pf induction ratings.

Thus, the resulting 1.0 pf synchronous motor efficiencies are generally higher than induction motor efficiencies for corresponding ratings.

Power Factor Correction

Power rates are based not only on the real power in KW consumed, but also on the power factor at which it is consumed. A penalty charge is made when the power factor is lower than a specified value (usually between 0.97 and 0.9 power factor). This is because a low power factor indicates an increase in reactive kilovolt amperes (KVAR) required and, consequently, an increase in the size of generating and distribution equipment.

Industrial plants generally have large lagging power factor loads such as smaller or low speed induction motors which require considerable amounts of KVARs in magnetizing (exciting) current. Although it is possible to use capacitors to supply the needed KVARs, it is often possible to use synchronous motors to adjust the plant's power factor. Because of their separate source of excitation, synchronous motors can either increase the KW base without requiring any additional KVARs (the unity pf motor) or, not only increase the KW base but also supply the needed KVARs as well (0.8 power or overexcited motor).

Thus, it can be seen that the synchronous motor can, in many instances, provide the user with the welcome reduction in power rates while providing the necessary drive horsepower.

Special Starting Characteristics

Usual requirements during the starting cycle may often be best met by synchronous motors, because combinations of special high or low torques and low inrush current can be furnished without appreciably affecting the motors operating characteristics.

Low inrush current at starting is often desirable because of power systems requirements. Some means of reduced voltage starting will always be available, but always at the expense of starting torque. In addition, there is the extra expense for the control equipment. Often times, sufficiently low inrush can be obtained by special design of the motor stator and amortisseur winding. In some cases, it is possible to lower line currents at starting by about 1/3 and still maintain the desired torque. However, it must be pointed out that applications involving high starting and pull in torque and/or high inertia loads require motor designs which at best have considerably higher than normal starting current.

Special Performance Characteristics

Constant Speed—Since the magnetic poles produced by the direct current applied to the field winding are locked by magnetic attraction to corresponding rotating (constant speed) magnetic poles produced by the stator armature winding, the rotor turns at a constant average speed. This is true regardless of the load applied to the motor or as long as the load stays within the pullout torque limitations of the motor. And not only will the synchronous motor maintain speed during overload, but it will also hold during voltage dips (again within specified overload torque limits).

Large Air Gaps—Synchronous motors inherently have a much larger air gap, at least twice that of the induction motor. This is often an advantage for mechanical reasons. The larger air gap also permits larger stator slots—an advantage when high voltage is required.

INERTIA AND TORQUES

Every synchronous motor must be designed with three different load torque conditions in mind:

- Starting torque to breakaway the load from rest.
- Pull in torque to accelerate the load to a speed from which the application of DC field excitation will pull it into synchronism.
- Pullout torque to keep momentary overload from pulling the motor out of synchronism when a momentary overload is imposed.

Although the synchronous motor operates with the DC field of the rotor locked in with the rotating field in the stator, it starts and accelerates by virtue of its amortisseur, or squirrel cage, winding which functions according to the same principals as the induction motor. Thus, the starting torque and the pull in torque (discussed below) vary as the square of the applied voltage, and the starting current varies directly as the voltage as is the case with the induction motor.

The pull in torque is defined as the maximum constant load torque against which the motor will pull its connected inertia (WK^2) load into synchronism when field excitation is applied. Since the synchronous motor starts as an induction motor, it will accelerate to the point where the motor torque just equals the torque required by the load. Usually this point is at 95 percent speed or greater (Figure 3). Now, if the DC field excitation is applied at the proper point, the rotor will "pull in" by acceleration, in a fraction of a revolution, the combined WK^2 of the motor rotor and the load to precisely synchronous speed.

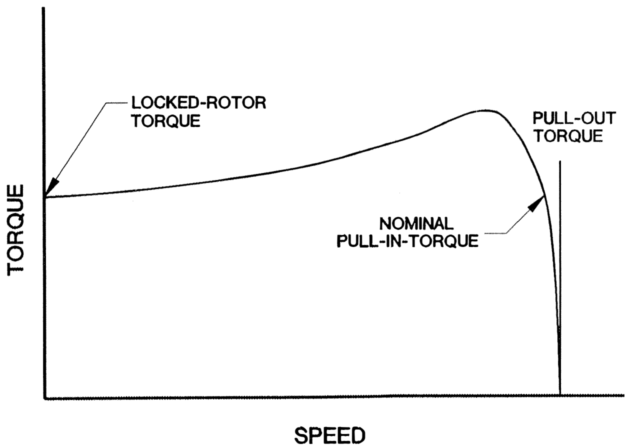

Figure 3. Synchronous Motor Speed Torque Characteristic.

The ability to accelerate the WK^2 (that is, "pull in" to synchronism) is limited for a given motor design. It becomes apparent, however, that for large values of WK^2, the amortisseur winding must bring the WK^2 to a higher speed than for small WK^2. Designing for this condition requires that the load torque be accurately known so that the speed torque capability of the amortisseur winding can be properly designed.

For example, consider a high inertia drive such as a compressor. The torque required by the compressor at nearly full speed is say 100 percent based on nameplate horsepower. Assume also, the usual motor does not develop sufficient synchronizing strength to synchronize this high WK^2 at any less than 98 percent synchronous speed. Should a motor with torque capability of 100 percent at 95 percent synchronous speed be applied to the compressor, the motor would fail to synchronize, because it would not be able to develop the required 100 percent torque at 98 percent speed. The typical speed torque curve on Figure 3 shows how motor torque capability drops as the motor nears synchronous speed.

In summary, any guarantee of pull in torque must be accompanied by the value of load WK^2 on which the guarantee is based. In addition to considering the effect of load WK^2 on acceleration into synchronism at near full speed, the motor designer must also consider the acceleration from zero speed to the pull in point. Higher load WK^2 required high energy input, and consequently, high heat loss in the amortisseur starting winding.

To compensate for this, motors with high WK^2 loads (five to fifty times normal) are built in larger frames to provide the accelerating capability. Also, as a consequence of high load WK^2, acceleration time becomes considerably extended.

The pullout, or maximum torque of a synchronous motor is unlike the induction motor breakdown torque in that no speed change occurs until the motor actually pulls out of synchronism. Since the amount of torque that can be sustained depends upon the strength of the two locked magnetic fields, any decrease in the strength of either will reduce the torque capability of the motor. Thus, a synchronous motor with a separate DC excitation source such as an M-G set or a shaft driven exciter will have its pullout torque vary discretely with the voltage change. But, if the excitation is of the static type which uses the AC supply as its power source, the excitation too, will decrease with line voltage drop. Since the pullout torque varies directly with field excitation, the total effect of line voltage variation on the pullout torque will be to the square of the voltage change. It must be noted that 0.8 pf motors with their larger fields generally have more pullout torque than 1.0 pf motors of the same horsepower and speed.

In the selection of a synchronous motor for specific application it is important to know the actual torque requirements. The starting and pull in torques should not be higher than necessary inasmuch as increased torques can only be had at the expense of an increase in starting current. This shows up as a more or less major disturbance of system voltage. On the other hand, some applications require considerably more starting and pull in torque than normal. Hence, a synchronous motor should be designed for a specific application.

LOADS AND OVERLOADS

In addition to specifying the horsepower rating, the frequency and severity of overloads, if any, should be described. When the motor load follows a duty cycle, care should be exercised in determining the horsepower rating of the motor. This is especially true because the average motor heating is not a direct function of the average horsepower. This is because the field current is normally maintained at rated value and the stator current does not drop linearly with load. As an example, as the load becomes essentially zero, the armature current drops from 100 percent at rated load to about 80 percent. So, although the horsepower output is zero, the stator current is 80 percent of rated load and the corresponding copper loss is about 64 percent of what it is at rated load.

EXCITATION

The requirement for a source of excitation for the synchronous motor must be included in the motor specification. There are two excitation systems generally available including (1) direct connected brushless exciters, (2) and slip ring excitation from a static source.

The modern synchronous motor with end shield mounted bearings generally has used a direct connected brushless exciter. This results in a compact unit with the exciter rotor pressed on a short shaft extension on the end opposite drive of the motor. The exciter stator is fitted to the motor end shield. For pedestal bearing construction, the exciter is usually best mounted on its own foundation or base pad, rather than "overhung" from the pedestal.

Slip ring motors usually obtain their excitation from a static exciter which is remotely mounted and converts AC to DC without any rotating elements. It usually is mounted with the motorstarting equipment. This method of excitation is fast becoming the most commonly used.

The brushless excitation method has the one outstanding feature of requiring no brushes in the DC circuit. The motor equipped with brushless excitation has, therefore, reduced maintenance costs since there are no brushes, collector rings, and exciter commutators. The brushless system is ideal for hazardous locations such as often are found with compressor applications. Brushless excitation has been successfully applied to low-speed pump drives where the reduced maintenance requirements are especially appealing.

SYNCHRONOUS MOTOR APPLICATIONS

Synchronous motors are used in practically all basic industries. The list below suggests the large number of uses for the synchronous motor.

Industry	*Synchronous Motor Applications*
Building	Pumps, air conditioning compressors
Chemical	Pumps, compressors
Lumber	Band Saws, pumps, compressors, gang saws
Machinery	Hydraulic press pumps, compressors
Mining	M-G sets for shovels, draglines and mine hoists, and pumps, fans, compressors
Power Plants	Blowers, feed-water and cooling-water pumps
Pulp and Paper	motor-generator sets, vacuum and water pumps, Jordans, refiners, beaters, defibrators, compressors, chippers, grinders
Rock Products	Ball mills, tube mills, crushers, pumps, compressors
Rubber	Rubber mills, compressors, Banbury mixers, pumps, plasticators
Steel	Motor-generator sets, ventilating fans, rolling mills, sintering fans, pumps, compressors
Textile	Pumps, compressors, MG sets
Water and Sewage	Pumps, compressors

While the above tabulation suggests that there are many "standard" applications, most synchronous motors are designed for their specific application. It is always in the user's best interest to give complete information including the actual torque required when specifying a synchronous motor.

INSULATION SYSTEM

The users of large electric motors and generators expect their equipment to give in the order of 20 to 40 years of reliable performance if properly operated and maintained. In the electric machine, no component is more important to its life than the electrical insulation system. This system, composed of nonmetallic materials, must provide electrical isolation and physical support of the electrical conductors for the expected life of the equipment, even though it is simultaneously undergoing gradual degradation.

The three major factors in the degradation of motor insulation are: (1) temperature; (2) voltage; and (3) mechanical force. Other factors such as moisture, abrasive particles, chemicals, and so forth may have dominant effects in specific application, but are of little significance in others. Where such factors are important, insulation system modifications are generally made to provide an acceptable degradation rate.

Improper operation, such as excessive overloads, stalling, and single-phase operation, is a major cause of motor failure. In such cases, rapid degradation of the insulation occurs, due primarily, to high temperature produced in the stator winding.

The selection of various insulation system components requires evaluating various materials item by item to determine likely candidates for an insulation system. These candidates must then be evaluated further as part of a system. Materials with good performance characteristics as a laboratory sample often turn out to be noncompatible with other system components or their capabilities may be altered drastically in the system.

What really matters is the system's performance. Insulation system tests are devised to verify all of the many necessary characteristics. These tests attempt to simulate real life service requirements, and to be of practical value. These tests must provide a meaningful evaluation in a relatively short time.

TEMPERATURE

Much confusion results in discussion of the thermal capabilities of motors because of a lack of agreement on definition of terminology. The following quotes from NEMA Standard MG 1 and from IEEE Publication Number 1 *General Principles for Temperature Limits in the Rating of Electrical Equipment* should assist in understanding the differences between rating materials and rating systems. IEEE Publications Number 1 is highly recommended reading for anyone wishing to delve into the total subject of insulation.

Material Temperature Index (IEEE Publication Number 1)

Many insulated parts of electric or electronic equipment do not operate at the maximum design temperature of the equipment. Therefore, it is recognized that materials of different temperature capabilities can be combined and will constitute a satisfactory insulation system. Such design techniques provide economic and performance advantages, but may lead to confusion in defining the temperature classification of the electric or electronic equipment if insulating materials and complete insulation systems are classified in the same way.

In the past, insulating materials have been placed arbitrarily in temperature classes. In modern technology, insulating materials are used in so may combinations and in so many ways that the concept of thermal classification for materials is no longer suitable.

A new method for designating the temperature capabilities of materials is described herein. This method effectively separates the temperature classification of insulation systems from the temperature capabilities of individual insulating materials. To indicate the relative temperature capability, insulating materials will be assigned a temperature index. The temperature index is related to the temperature at which the material will provide a specified life as determined by test or as estimated from service experience.

For practical reasons, and to provide continuity with past procedures, it is reasonable that thermal indices for insulating materials be grouped under preferred nominal numbers as given in the following table; however, responsible technical committees may elect to use other numbers:

Number Range	Preferred Temperature Index
90 to 104	90
105 to 129	105
130 to 154	130
155 to 179	155
180 to 199	180
200 to 210	200
220 and above	No preferred indices have been established

The temperature indexes are a guide and do not imply a thermal classification of a limitation on use in equipment. Temperature classification for the purpose of rating electric machines should be defined in terms of the thermal endurance of the insulating system.

Classification of Insulation Systems (NEMA MG 1-1.65)

An insulation system is an assembly of insulating materials in association with the conductors and the supporting structural parts of a motor or generator. Insulation systems are divided into classes according to the thermal endurance of the system for temperature rating purposes. Four classes of insulation systems are used in motors and generators, namely, Classes A, B, F, and H. These classes have been established in accordance with the IEEE *General Principles for Temperature Limits in the Rating of Electric Equipment, Publication Number 1.*

Insulation systems shall be classified as follows:

A specific class insulation system is one which by experience or accepted test can be shown to have suitable thermal endurance when operating at the limiting class temperature specified in the temperature rise standard for the machine under consideration.

"Experience" as used in this standard, means successful operation for a long time under actual operating conditions with the machine temperature rise at or near the temperature rating limit.

"Accepted test" as used in this standard, means a test on a system which simulates the electrical, thermal, and mechanical stresses occurring in service.

Where appropriate to the construction, tests shall be made in accordance with the following applicable IEEE test procedures:

- Evaluation of Systems of Insulating Materials for Random-wound Electric Machinery, Std 117.
- Evaluation of Systems of Insulating Materials for AC Electric Machinery Employing Form-wound Preinsulated Stator Coils, Std 275.
- Evaluation and Classification of Insulation Systems for DC Machines, Std 304.
- Evaluation of Sealed Insulation Systems for AC Electric Machinery Employing Form-wound Stator Coils, Std 429.

For other constructions for which tests have not been standardized, similar procedures may be used if it is shown that they properly discriminate between service-proven systems known to be different.

When evaluated by an accepted test, a new or modified insulation system shall be compared to an insulation system on which there has been substantial service experience. If a comparison is made on a system of the same class, the new system shall have equal of longer thermal endurance under the same test conditions. If the comparison is made with a system of lower temperature class, it shall have equal or longer thermal endurance at an appropriately higher temperature. When comparing systems of different classes, an appropriate higher temperature shall be considered to be 25 C per class higher than the temperature for the base insulation system class.

TESTING PROCEDURE

The changes in the characteristics of insulating materials with time when subjected to elevated temperature generally follows the classic Arrhenius rate-of-reaction equation. This chemical deterioration may take different routes, such as by increased molecular cross linking with resultant embrittlement, or by molecular breakdown, with subsequent loss of material as volatiles, which in either example could lead eventually to physical disruption of the dielectric.

Most users are familiar with the summary of this concept, which is the rule of thumb that a machine operated at a nominal temperature will have twice the thermal life of an identical machine operated at a temperature 10°C higher.

Model stator sections are tested to predict the thermal capabilities of insulation systems by comparison with service-proved systems under identical simulated operating conditions. For example, a vacuum pressure impregnated micaeous system was tested according to IEEE Std 275 and to IEEE Std 429, as a sealed system.

VOLTAGE ENDURANCE

The life of an insulation system subjected to aging under voltage is an inverse function of the applied voltage stress and frequency. Insulation breakdown is believed to be due to localized erosion caused by (1) corona pulses, the pattern of which repeats every cycle of applied voltage; and (2) chemical attack from the oxidation products resulting from ionization of the air in the voids in the insulation system.

The applied voltage is a factor which influences insulation life. The life varies with motor voltage, depending upon the ratio of operating voltage to the corona start (or corona extinction) voltage. The operating voltage is generally below corona start for motors rated four kV and less. While a voltage transient may trigger ultimate insulation failure, transient voltage is usually not considered a major factor in insulation degradation.

MECHANICAL FORCES

The insulation on coils is subjected to high mechanical forces during motor starting, due to rapid temperature changes which cause differential expansion of the conductors relative to the iron core. To be assured that new insulation systems are at least equivalent to service-proven systems, coils in a model stator are subjected to current-inrush testing which produces thermal forces of the same kind but of greater magnitude than the forces acting on the insulation structure during motor starting. A current density of approximately 25000 amp/in^2 is imposed on the coils for 20 seconds followed by a cooling period. Due to the duration of the current application period and to the temperature reached by the copper (approximately 190°C), this simulated starting cycle is more severe than normally found in service. A test sequence consists of thermal aging the model followed by inrush-current cycling. While wet from a moisture exposure of 48 hours at 100 percent relative humidity plus dew, it is electrically proof tested. The results show the heat distortion or deformation temperature of the resin needed to have a maximum limit to accommodate the strain without fracture. The resin selected for impregnation of the micaeous structure must retain its heat distortion temperature below the critical value after thermal aging. The resin impregnate and the micaeous layers become a compatible composite.

PRODUCT QUALITY ASSURANCE

The intrinsic quality of the stator coil insulation system was determined by test, first by materials selection tests then by tests of the composite system.

With intrinsic quality proven, the product quality must be maintained in the production of the electric machine. Coils and windings should be tested during the stages of manufacture at voltages much greater than the final high potential test specified by ANSI/NEMA Standards. These in process high potential tests should be conducted before the insulation is impregnated with resin to detect deficiencies in the primary insulation which otherwise might be masked by the impregnating resin's ability to greatly increase the composite dielectric strength.

ENVIRONMENTAL CONSIDERATIONS

The environmental conditions in which a motor will operate must be carefully evaluated to determine not only the type of enclosure to be used, but also the type of insulation treatment that is required. Thus, a proper motor specification will contain details about environmental conditions such as dust, abrasive grit, conductive materials, chemicals, moisture, and in some cases, temperature extremes. Although the motor manufacturer may be able to guess the environmental conditions by the application and the industry served, there are often unique aspects for the particular application which may alter what is to be expected. To ensure there is no misunderstanding, it is always best to fully describe the application and environment.

Modern insulation systems have inherently remarkable qualities as compared with the old cotton and paper wrappings impregnated with asphalt and shellac. In some applications, insulation has become so good that the degree of motor enclosure can be reduced without adversely affecting motor reliability.

Abrasion

In atmospheres where abrasive dusts (such as fly ash) are present, many insulation systems are quickly worn away by the sand blast effect of the air borne particles leaving the fan and other rotating parts at high velocity. Tough as the epoxies have been found to be, it is necessary, where such abrasive conditions exist, to use a resilient over coating to ensure the necessary long insulation life. Manufacturers can apply this treatment whenever the threat of abrasion is present.

Sealed Insulation

The foremost achievement in special insulations is probable "sealed insulation." The advent of the new resins such as the polyesters and especially the epoxies has enabled most manufacturers to achieve a stator winding which can comply with the NEMA definition.

A machine with sealed windings is an alternating current squirrel cage machine making use of form-wound coils and having an insulation system which through the use of materials, processes, or a combination of materials and processes result in a sealing of the winding against contaminants. This type of machine is intended for exposure to more severe environmental conditions than the usual insulation system can withstand. Other parts of the machine may require protection against such environmental conditions.

CONCLUSION

The selection and specification of a large industrial AC motor has been discussed. The performance, economic advantages, and limitations of various design induction motors and synchronous motors were presented. While this discussion is introductory in nature, it provides a sound basis for developing a detailed specification for a particular motor application.

Additional topics, many of which are related to the mechanical nature of the electric machine such as: bearing design, critical speeds, frame/structural rigidity, seal design, noise, and ventilation have been discussed from the point of view of turbomachinery by other authors. In general, the analysis techniques described by these authors apply directly to the industrial motor. The user needs to determine early in the specification and selection process what these requirements needs to be since the mechanical structure of a motor is the difficult part for the manufacturer to change. Various professional society specifications have been prepared to address the various mechanical design concerns. In some cases, these concerns have resulted in field complaints by users. The trend in recent years to purchase large motors as an industrial commodity, selected from a catalog has gone a long way to facilitate problems which an applications study and specification could have easily avoided.